In situ observation of reversible rippling in multi-walled boron nitride nanotubes

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Abstract
The recent observation of high flexibility in buckled boron nitride nanotubes (BNNTs) contradicts the pre-existing belief about BN nanotube brittleness due to the partially ionic character of bonding between the B and N atoms. However, the underlying mechanisms and relationships within the nanotube remained unexplored. This study reports for the first time the buckling mechanism in multi-walled BNNTs upon severe mechanical deformation. Individual BNNTs were deformed inside a transmission electron microscope (TEM) equipped with an in situ atomic force microscopy holder. High-resolution TEM images revealed that bent BNNTs form multiple rippling upon buckling. The critical strain to form the first ripple was measured as 4.1% and the buckling process was reversible up to 26% strain. As opposed to carbon nanotubes, the BNNTs buckled into V-shaped ripples rather than smooth wavy shapes. The rippling wavelength was quantified in terms of the outer diameter and thickness of the nanotubes. The BNNTs showed a larger rippling wavelength compared to that of CNTs with the same number of walls. This difference was explained by the tendency of BN structures to reduce the number of thermodynamically unfavorable B–B and N–N bonds at the sharp corners in the rippling regions. The BNNTs’ structure also exhibited a higher fracture strain compared to their counterpart.

(Some figures in this article are in colour only in the electronic version)

List of symbols

\[ \lambda \] Buckling wavelength
\[ \varepsilon \] Strain
\[ \nu \] Poisson ratio
\[ h \] Wavelength of buckling
\[ r \] Radius of nanotube
\[ R \] Radius of curvature

1. Introduction

The mechanical properties of boron nitride nanotubes (BNNTs) are measured and calculated both theoretically [1, 2] and experimentally [3, 4] to be in the same range as those of carbon nanotubes (CNTs), their structural analogue. However, they exhibit important advantages over CNTs, such as higher thermal/chemical stability [5] and thermal conductivity [6, 7]. In addition, their electronic properties are independent with respect to chirality, diameter, or nanotube length [8]. BNNTs offer a variety of applications in nano-scale electronic devices [9, 10], optoelectronics [11], and as a reinforcement in composites [12]. Despite the potential impact of BNNTs in many areas of science and industry, a robust understanding of their mechanical behavior is lacking and thus limits the design and optimization of BNNT-enhanced materials.

There are numerous reports on the mechanical responses of single- [13] and multi-walled CNTs [14–16]. CNTs embedded in matrices [17, 18], or under torsion force [19]. Iijima et al [20] first observed single kinks in single-walled CNTs of diameters 0.8 and 1.2 nm bent to large angles.